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Sand Bed Load in a Brook Trout Stream[1]

GAYLORD R. ALEXANDER

Michigan Department of Natural Resources, Hunt Creek Fisheries Research Station Route 1, Post Office Box 122, Lewiston, Michigan 49756, USA

EDWARD A. HANSEN

U.S. Forest Service, North Central Forest Experiment Station, Forestry Sciences Laboratory Post Office Box 898, Rhinelander, Wisconsin 54501, USA

Abstract.—An experimental introduction of sand sediment into Hunt Creek in the northern Lower Peninsula of Michigan that increased the bed load 4–5 times resulted in a significant reduction of brook trout (*Salvelinus fontinalis*) numbers and habitat. The brook trout population declined to less than half its normal abundance. The growth rate of individual fish was not affected. Population adjustment to the poorer habitat was via a decrease in brook trout survival rates, particularly in the egg to fry and/or the fry to fall fingerling stages of their life cycle. Habitat for brook trout and their food organisms became much poorer, as judged by the drastic reductions of both. Stream morphometry changed considerably, the channel becoming wider and shallower. Furthermore, sand deposition aggraded the streambed and eliminated most pools. The channel became a continuous run rather than a series of pools and riffles. Water velocities increased, as did summer water temperatures. Relatively small sand bed-load concentrations of only 80 ppm had a profound effect on brook trout and their habitat.

Trout streams in the upper midwest of the United States are typically low-gradient streams which have slow to moderate velocity. Some of these streams have excessive sand on the streambed. Other streams, with somewhat steeper gradients, have less sand deposited but yet may have considerable sand in transport. Abnormally large amounts of human-induced sediments or sediments associated with catastrophic floods may be detrimental to trout habitat (Cordone and Kelley 1961). However, prior to this study, we did not know the effect of low levels of moving sand bed load on trout and trout habitat. In initiating this and other sediment–trout studies in Michigan, we speculated that low concentrations of sand bed load in low-gradient streams have measurable adverse effects on the habitat of stream fishes in general and trout in particular.

The presence of sand is deceiving in that it does not produce the turbidity commonly associated with severe stream sedimentation. Even substantial amounts of moving sand bed load are not readily apparent in steep-gradient streams. Only when the gradient is low enough for deposition to occur does the sediment become evident by the presence of sand-filled reaches. Sampling with a hand-held, DH-48 suspended-sediment sampler (U.S. Interagency Committee on Water Resources 1963) over a natural streambed in low-gradient streams will miss much of the bed load. This may lead inexperienced observers to erroneously conclude there is no significant sediment discharge when, in fact, there may be considerable sand moving in the unsampled zone adjacent to the streambed. A modified procedure of sampling with a DH-48 sampler over sills or weirs (Hansen 1974), or with a sampler designed specifically for sampling bed load (Helley and Smith 1971), will assess more realistically the presence of sand bed load.

Sandy bed load may decrease food supplies of trout by scouring or burying desirable substrate, destroy cover by aggrading channels and filling pools, and reduce spawning success by covering or plugging gravels. The "finer" suspended sediments also negatively affect some of these same aspects of fish habitat. Consequently, reducing the stream sediment load is often a major objective of fish habitat improvement programs.

In this paper, we report on a 15-year field test in a brook trout (*Salvelinus fontinalis*) stream where 5 years of pretreatment study were followed by 5 years when sand was added daily to the stream and then by 5 more years when sand was not added. The effects of this added sand on both the stream morphometry and the brook trout population were measured. The results of this study are compared with those of a companion study we did on another stream where the moving sand bed load was removed with a sediment basin (Alexander and Hansen 1982; Hansen et al. 1982).

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Study Area

This study was conducted at the Michigan Department of Natural Resources' Hunt Creek Fisheries Research Station in the north-central Lower Peninsula of Michigan near the village of Lewiston. Hunt Creek is a small 20-ft^3/s trout stream that flows through sandy glacial-drift country. The deep sand and gravel drift produce little surface runoff, high groundwater, and, consequently, extremely stable stream discharges. For example, records for the Thunder Bay River near Hillman, of which Hunt Creek is a major tributary, show that the stream discharge that is exceeded 2% of the time is only 4.4 times greater than that exceeded 98% of the time (Velz and Gannon 1960). The stable supply of cold groundwater (47–49°F) and low stream gradient are typical of trout streams throughout much of the northern part of the Lower Peninsula of Michigan. The sediment concentrations in Hunt Creek were lower than the average of many streams we sampled. The fish population of Hunt Creek was predominantly brook trout with a moderate population of mottled and slimy sculpins (*Cottus bairdi* and *Cottus cognatus*). Other fish species were rare.

Methods

The stream was divided into two contiguous 1-mi sections, sand was added to the lower section and the upper section served as a control or reference section (Figure 1). "Treatment" consisted of increasing the stream's total sediment concentration from approximately 20 ppm (primarily sand bed load) to 80 ppm to simulate concentrations found in larger trout streams with severe streambank erosion (Hansen 1971). Sand was added daily at the upstream end of the treated section for a period of 5 years at a rate that increased the sediment load four times over that normally present. The amount added was varied with stream discharge to simulate natural sediment delivery patterns to the stream. Although the once-a-day input created a slug effect at the input point, the slowly moving sand dissipated that effect within a short distance downstream.

Fifteen years of brook trout population data were used to determine the response of fish to sediment. The population data included five pretreatment years, a 5-year period of sand input, and a 5-year post-treatment period with no sand input. Thus, comparisons of fish populations were made between treated and controlled sections before, during, and after treatment. At times we will refer to the entire 10-year period following initial sand bed-load introduction as treatment effect because the impact of added sand was evident throughout the 10-year period, although no sand was added the last 5 years. Because the entire experimental area was closed to fishing, only natural mortality affected the brook trout population aside from the controlled sampling of fish in both the treated and control sections for diet analysis.

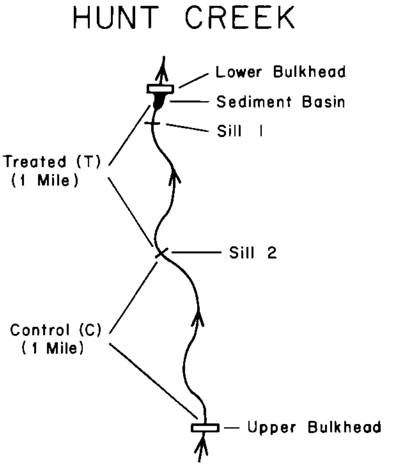

FIGURE 1.—Diagrammatic presentation of the study area in Hunt Creek, Michigan.

A stream gauging station with a water-level recorder was established to provide a measure of mean daily flow, and staff gauges were installed at two sediment-sampling stations. The stations were located so that the sediment discharge entering and leaving the treated section was sampled (Figure 1). Sediment samples were collected over a 10-year period including 1 year before, 5 years during, and 4 years after the sand-input period. Sediment samples were collected weekly by sampling with a DH-48 suspended-sediment sampler over 2 × 12-in wooden sills in such a manner that the sampler intake traversed the entire vertical profile of flow (Hansen 1974). Samples collected in this manner provided a measure of the total sediment discharge.

Yearly supplies of sand were stockpiled at the upstream end of the treated section. Samples of bed material and samples from the sand borrow area were analyzed for particle size distribution and matched for a similar size distribution. Starting October 1, 1971, sand was added, usually once a day, to the stream with an endloader. The quantity added was three times the daily sediment discharge. Based on sediment sampling during the one pretreatment year, a "sediment input table" was developed which gave daily sediment input in cubic yards based on stream discharge. Several times a year the content of the endloader bucket was weighed and converted to volume of sand, based on the sampled bulk density adjusted for moisture and gravel content. This calculated volume provided a check on the equipment operator's estimates of sand input. The sand contained a small amount of gravel which gradually formed a gravel riffle at the input point. These gravel deposits were removed with a backhoe whenever the damming effect became excessive and they were replaced with an equal volume of sand added over several days with the normal input of daily sediment. The sand was trapped at the lower end of the 1-mi treated section in a 25 × 200-ft sediment basin. The basin was cleaned with a dragline periodically throughout the study. During the first 4 years of the treatment period, the basin was surveyed before and after each cleanout by "leveling" on a 5-ft grid of points. These data permitted calculation of the volume of deposits trapped by the basin, thus providing another measure of sediment discharged from the treated section.

Changes in stream morphometry were determined by establishing permanent cross sections at 100-ft intervals along the entire 2-mi study section of stream. These cross sections were surveyed annually from 1971 through 1977 and again in 1980. At each cross section, a stake was set permanently on each bank. A third stake was buried in the streambed as a benchmark to determine if either of the bank stakes had moved since the initial survey. A steel measuring tape was then stretched at a measured tension between the two bank stakes, and the distance from the tape to the streambed was measured at all major slope breaks in the channel cross section. The streambed also was subdivided into widths as narrow as 1 ft and classified as to streambed particle size (sand, gravel, cobble), biological materials (vegetation, wood, detritus), or various combinations thereof. These data permitted the calculation of changes in channel scour and fill, cross-sectional water area (the static water volume in the channel reach), and streambed composition. A "leveling" survey also was made between selected cross sections along the treated section. From this survey, the water surface profile was drawn and then updated with each cross section remeasurement.

A water temperature recorder had been placed at the downstream end of the treated section many years prior to treatment. Maximum–minimum thermometers distributed throughout the study area were read weekly.

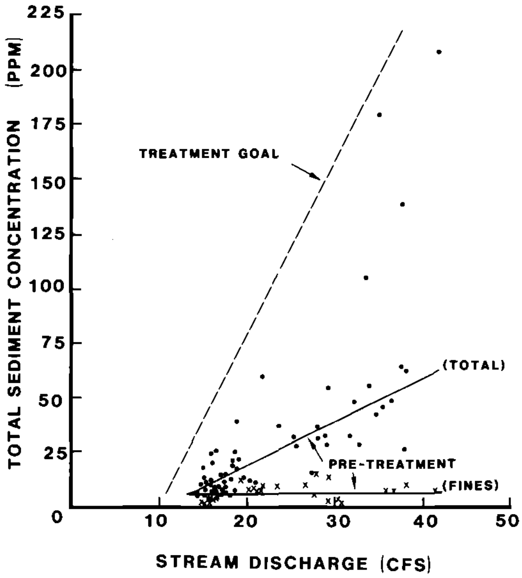

FIGURE 2.—Relationship of the pretreatment total sediment concentration to stream discharge in ft^3/s (cfs) in the treated section of Hunt Creek.

Spring and fall brook trout population estimates were made from electrofishing data, beginning in the fall of 1967 and extending through the fall of 1981. Estimates were stratified by 1-in-size groups and calculated by the Petersen mark–recapture method. Representative samples of brook trout scales were used to apportion estimates by length group to estimates by age group. Mortality rates were computed from sequential estimates of age groups. The average length by age group was determined following the procedure described by Alexander and Ryckman (1976). Growth rates were computed from sequential estimates of the average size of brook trout by age group.

Brook trout were collected by electrofishing for stomach analyses during 1972 and 1981 for ten 2-week periods during their major growing season, beginning with the last Saturday in April. Ten 3- to 4-in, ten 5- to 6-in, and five 7- to 8-in brook trout were collected during each 2-week period for annual samples of 100, 100, and 50 fish, respectively, from both the control and treated sections. Stomachs were preserved in 10% formalin until hardened, after which the contents were transferred to 80% alcohol for analysis; both number and volume of food taxa were determined. The fish collections also were used to monitor any changes in length–weight relationships.

Samples of stream invertebrate benthos were collected monthly from April through September

TABLE 1.—Volume of sediment added to Hunt Creek, 1972–1976.

Water year (beginning Oct 1)	Volume (yd^3)
1972	870
1973	824
1974	754
1975	770
1976	1,005
Total	4,223

with a standard Surber sampler. Five samples were taken each month from four stations. Two stations were located in the treatment section and two in the control section. Samples were taken at sites spaced equal distances across the stream transects. Invertebrates were picked using sugar flotation (Anderson 1959). Both number and volume of benthos per square foot of stream bottom were determined.

We used a ratio analysis technique (Shetter and Alexander 1962; Alexander and Hansen 1982) to test for changes in brook trout population characters, food content of fish stomachs, benthic invertebrate communities, and water temperatures. These T/C ratios were calculated by dividing the variable for the treated (T) section by that for the control (C) section for each year. The ratios for the pretreatment years then were compared to ratios for the treatment or post-treatment years by analysis of variance or regression analysis.

Stream and Sediment Discharge before Treatment

Stream discharge at the upstream end of the treated section (sill 2) averaged 20 ft^3/s and ranged from 14 to 50 ft^3/s. Downstream, at sill 1, it averaged 25 ft^3/s, or 25% greater. Three small tributaries, totaling about 3 ft^3/s, enter between the two stations; the balance of the increased flow originates from groundwater. These sources of additional streamflow do not add much sediment, and sediment concentration actually decreases from 20 ppm at sill 2 to 14 ppm at sill 1, primarily because of dilution from inflow of the nearly sediment-free water. Total sediment discharge calculated from measurements was 390 tons per year at sill 2 and 350 tons per year at sill 1. This is a 10% decrease in sediment load between the two stations and is judged to be not significant due to limitations inherent with this type of data. However, a decrease in sediment load is possible if there was a net accumulation on the streambed—in this case, an average of about 0.01 ft over the entire channel.

Of the 20-ppm total sediment concentration at sill 2, 5 ppm (25%) was silt and clay and the remaining 15 ppm was sand. The concentration of the fines did not increase with higher streamflows, but rather stayed at a fairly constant level over the entire range of streamflow (Figure 2). All of the increased sediment concentration with higher stream discharges was due to increased movement of sand.

Sediment Input

Sediment input totaled 4,223 yd^3 over the 5 years (Table 1) or an average of about 2.3 yd^3/d (845 yd^3/year). The data in Table 1 include a small fraction of gravel and are not adjusted for the final higher density the sediment acquired when in place on the streambed.

An increase in sediment concentration was not noted at sill 1, near the lower end of the treated section, until June 1973—21 months after the start of daily additions of sand nearly 1 mi upstream (Figure 3). This increase indicated that sand added to the stream had finally traversed the length of the treatment section, and that essentially all of

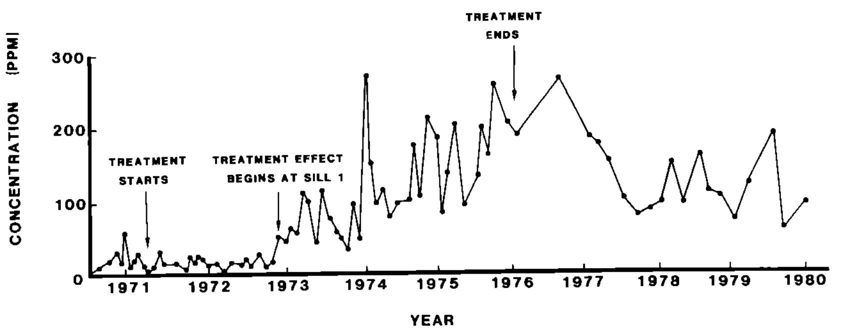

FIGURE 3.—Sediment concentration at sill 1. Points for 1971–1976 are means of five samples collected at approximately weekly intervals; points for 1977–1980 are means of two samples collected at monthly intervals.

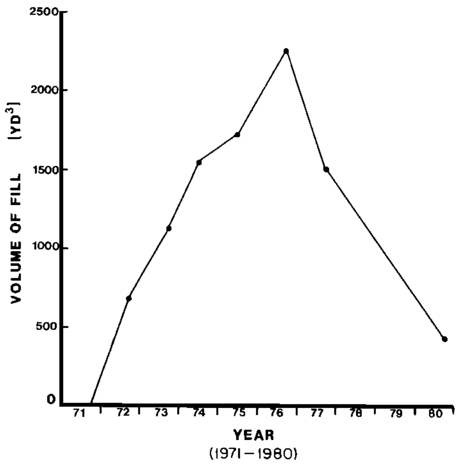

FIGURE 4.—Cumulative channel fill with sand as calculated from change in streambed elevation in the treatment section of Hunt Creek.

the sand (1,300 yd³) added during the first 21 months went into channel deposits.

Channel Deposits

The volume of sand deposits on the streambed increased throughout the 5-year sand-input treatment period (Figure 4). The increasing channel fill over time at the survey cross sections is shown in Figure 5. Large differences in fill among cross sections were the result of the initial streambed configuration. Deep deposits were added to the pools; stream "run" sections had less deposition.

Increases in bed elevation due to deposition demonstrate the progression of the zone of maximum channel deposition during the treatment period (Figure 5). Deposition during the first year was primarily in the upper 2,200 ft of the channel (see 1972 line). Deposition during the last 2 years (from 1974 to 1976) was greatest between about 900 and 2,900 ft. By 1980, 4 years after treatment ended, the upper section of the stream had recovered to near its initial elevation. However, substantial channel fill, which averaged about 0.25 ft, still remained between the 1,700- and 3,000-ft sections.

As the sand "wave" gradually progressed downstream, the streambed and water surface rose. The streambed was elevated an average of 0.64 ft by the end of the treatment period (Table 2) and the water surface elevation had increased by 0.5–0.75 ft throughout the upper two-thirds of the treated

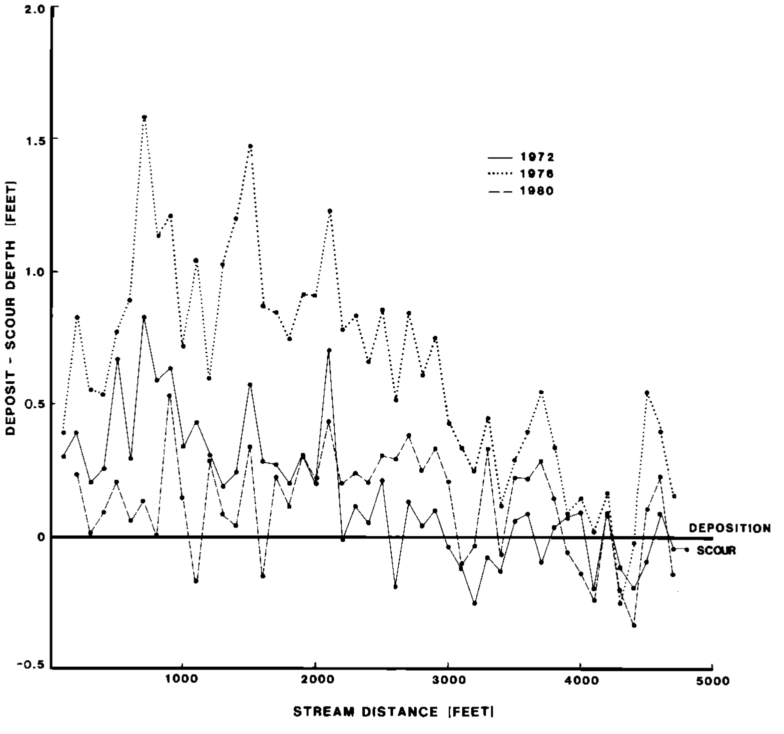

FIGURE 5.—Trends in channel sand deposition or scour from 1971 baseline survey data taken at 100-ft intervals along the treated section of Hunt Creek for selected years. Depths are averages for each stream cross section.

TABLE 2.—Channel geometry changes relative to June 1971 base period. (The 1971 stream widths and water volumes are given to provide a comparison for subsequent changes.)

Year	Water elevation Control (ft)	Water elevation Treated (ft)	Bed elevation Control (ft)	Bed elevation Treated (ft)	Stream width Control (ft)	Stream width Treated (ft)	Water volume Control (yd^3)	Water volume Control (%)	Water volume Treated (yd^3)	Water volume Treated (%)
1971					13.4	19.4	1,665	100	4,662	100
1972	−0.01	+0.02	−0.002	+0.15	+0.2	+0.3	+36	+2	−467	−10
1973	−0.05	+0.12	+0.002	+0.31	+0.2	+0.9				
1974			+0.002	+0.45	+0.2	+1.5				
1975	−0.05	+0.24	−0.040	+0.47	+0.3	+1.4	+64	+4	−883	−19
1976	−0.07	+0.33	−0.020	+0.64	+0.0	+1.3	+12	+0.7	−1,136	−24
1980	−0.13	−0.03	−0.090	+0.13	+0.1	−0.3	−41	−3.1	−606	−13

section. As the water surface became higher than its initial datum, the stream width increased, and as the channel gradient steepened, the water velocity increased. The greater water velocity, together with pool filling, resulted in a reduced cross-sectional water area and, therefore, reduced static water volume. Maximum fills of more than 3 ft occurred in some pools which were at those cross sections with maximum deposit thickness shown in Figure 5. Average stream depth decreased 0.31 ft by the end of the treatment period. Almost all of the change in stream depth was due to a reduction in areas deeper than 1.25 ft (Figure 6). Areas deeper than 2 ft were reduced 86% (from 17 to 2% of the streambed area). There was essentially no change in stream depth in the control section throughout the study period.

Stream width increased 1.3 ft. This was a conservative figure because the stream was out of its low marshy banks over a considerable distance and most of the very shallow "over-bank" width is not included. Static water volume decreased by a maximum of 24% (Table 2). Channel gradient between sill 1 and sill 2 increased from an initial 0.00081 to 0.0099 (from 4.3 to 5.2 ft/mi) and acquired a more uniform slope.

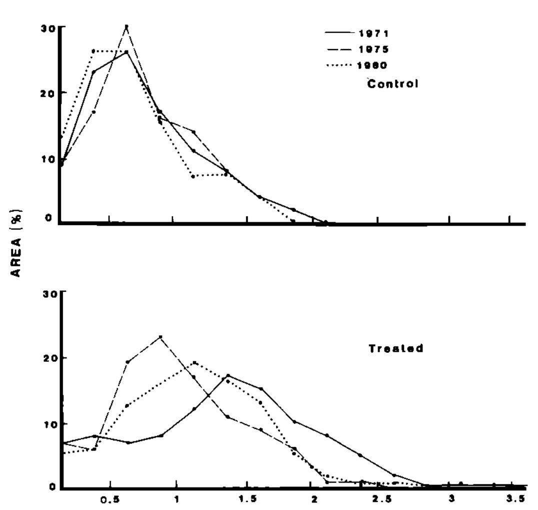

FIGURE 6.—Distribution of water depths for the control and treated sections of Hunt Creek.

Streambed Composition

As expected, the introduction of sand produced a sizeable increase in sand-covered streambed. Sand areas increased from the initial 40% up to 68% of the area and gravel decreased from 17% down to 5% during the first 4 years of treatment (Table 3). These bed types showed no trends in the control area during the same period. Areas with vegetation, wood, detritus, or various combinations of streambed types showed large fluctuations from year to year but no definite trend. This could be due either to actual changes in their area or to changes in observer bias from year to year. Many vegetation beds were buried by fairly thick sand deposits. However, the vegetation eventually penetrated the deposits and reestablished itself in much of its former area but it was less dense.

Stream Recovery

After the termination of sand input, the stream channel gradually reverted towards its initial con-

TABLE 3.—Streambed composition of Hunt Creek as percent of area in June 1971–1975.

Year	Control Sand	Control Gravel	Treated Sand	Treated Gravel
1971	16	63	40	17
1972	16	57	52	12
1973	9	58	50	9
1974	20	61	59	7
1975	14	59	68	5

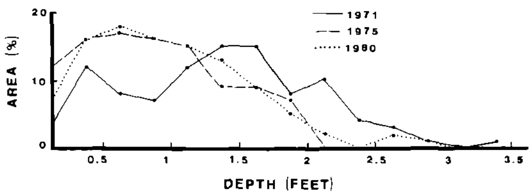

FIGURE 7.—Distribution of water depths within 3 ft of the bank in the treated section of Hunt Creek.

dition. By 1980 (4 years after the end of sand input), the average streambed elevation had returned to near normal over much of the treated section (Figure 5). Most of the remaining section of elevated bed was in the general area of 900 to 2,900 ft from the input point. This coincided roughly with the area of elevated water surface between 1,100 and 2,800 ft. Although the streambed elevation was near its original datum in the lower end of the stream, the water surface elevation was considerably lower than its initial elevation. This lower water surface, due to increased water velocity, resulted from the elimination of vegetation and the covering of rocks, logs, and other obstacles with sediment which reduced friction. Consequently, the net reduction in water volume in the treated section was still 13% or just slightly more than half of what it was at the peak of the treatment effect in 1976 (Table 2).

There was some increase in water depths 4 years after the sand input period ended. The area of stream with depths between 0.5 and 1.0 ft decreased with a commensurate increase in depths of 1.0–1.75 ft (Figure 6). There was essentially no recovery in depths greater than 1.75 ft (i.e., the deep pools had not been scoured out during the 4-year recovery period).

The sand bed load moved primarily along the main flow line of the stream during the first few years of treatment. Then, in a period of over a year it gradually spread laterally, eventually filling in the stream near the banks. By the end of the sand-input period, stream areas deeper than 2 ft that were within 3 ft of the bank had been eliminated (Figure 7). The process reversed itself after sand input ended. Sand was scoured out from the main flow line of the stream but little was removed from the stream edges. Although a lot of sand was scoured out of the treated section by 1980, there was essentially no recovery of the deeper stream depths near the banks.

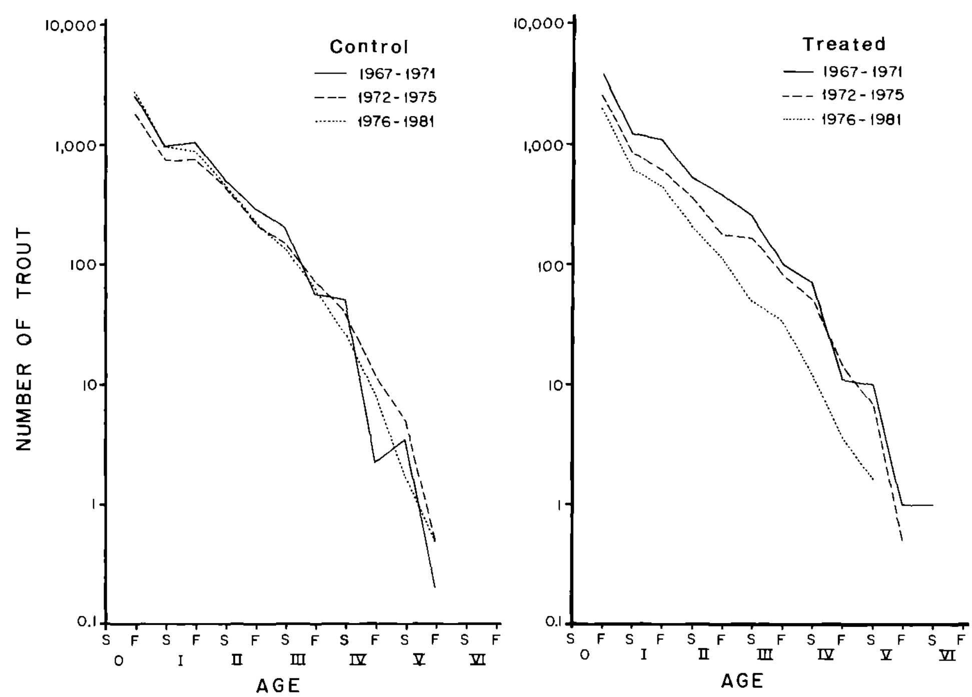

FIGURE 8.—Survivorship curves for brook trout in the control and treated sections of Hunt Creek in the spring (S) and fall (F).

TABLE 4.—Estimated numbers of brook trout, by length group, in the fall (1967–1981) and in the spring (1968–1981) in the treated area of Hunt Creek.

	Fall				Spring			
	Length group (in)				Length group (in)			
Year	2.0–4.9	5.0–7.9	8.0+	Totals	2.0–4.9	5.0–7.9	8.0+	Totals
1967	3,821	739	287	4,847				
1968	4,151	750	197	5,080	1,276	424	139	1,839
1969	5,192	1,342	393	6,927	1,258	641	145	2,044
1970	3,294	917	293	4,504	1,538	663	236	2,437
1971	4,079	1,133	367	5,579	1,096	617	190	1,903
1972	2,680	743	367	3,790	880	485	286	1,651
1973	3,668	597	212	4,477	1,184	487	307	1,978
1974	2,278	381	116	2,775	701	220	132	1,053
1975	2,065	428	83	2,576	784	183	56	1,023
1976	1,957	326	81	2,364	551	228	58	837
1977	2,596	223	34	2,853	731	166	37	928
1978	1,407	464	111	1,982	721	139	25	885
1979	1,716	428	170	2,314	480	220	31	731
1980	2,686	307	95	3,088	320	157	86	563
1981	2,314	464	55	2,833	921	265	83	1,269
Pre-treatment average (1967 or 1968–1971)	4,107	976	304	5,387	1,292	586	178	2,056
Transitional average (1972–1975)	2,673	537	194	3,404	887	344	195	1,426
Treatment average (1976–1981)	2,113	369	91	2,573	621	195	53	869

Water Temperature

Water temperatures in the control section were warmer in the winter but cooler in the summer during the 1972–1981 treatment period as compared to the 1961–1971 period. Water temperatures in the treated section during the 1972–1981 period likewise were warmer in the winter but, in contrast to the control section, also were warmer during the summer. Spring and fall temperatures were relatively unchanged in both sections.

TABLE 5.—Estimated numbers of brook trout, by length group, in the fall (1967–1981) and in the spring (1968–1981) in the control area of Hunt Creek.

	Fall				Spring			
	Length group (in)				Length group (in)			
Year	2.0–4.9	5.0–7.9	8.0+	Totals	2.0–4.9	5.0–7.9	8.0+	Totals
1967	2,561	680	157	3,398				
1968	3,123	865	169	4,157	1,141	527	115	1,783
1969	3,458	900	179	4,537	1,021	612	88	1,721
1970	3,024	814	146	3,984	1,000	628	107	1,735
1971	3,022	818	134	3,974	1,122	580	101	1,803
1972	2,691	692	134	3,517	1,152	474	114	1,740
1973	2,081	631	127	2,839	1,084	518	86	1,688
1974	1,784	586	122	2,492	873	463	105	1,441
1975	1,947	538	103	2,588	423	239	75	737
1976	2,220	733	150	3,103	727	352	69	1,148
1977	3,479	482	130	4,091	774	229	77	1,080
1978	2,823	812	165	3,800	963	265	69	1,297
1979	3,388	827	144	4,359	1,099	511	126	1,736
1980	3,036	662	100	3,798	1,599	523	130	2,252
1981	3,941	776	103	4,820	1,391	572	105	2,068
Pre-treatment average (1967 or 1968–1971)	3,038	815	157	4,010	1,071	587	103	1,761
Transitional average (1972–1975)	2,126	612	122	2,860	883	424	95	1,402
Treatment average (1976–1981)	3,148	715	132	3,995	1,092	409	96	1,597

TABLE 6.—Ratios (±95% confidence limits) of treated-to-control areas (T/C) for numbers of brook trout present in the fall and spring, before and during sedimentation, by length group. Percent changes (±95% confidence limits) in brook trout numbers between the pretreatment (1967 or 1968–1971) and treatment (1976–1981) periods are included.

Period	Length group (in) 2.0–4.9	5.0–7.9	8.0+	Totals
		Fall		
Pretreatment 1967–1971	1.35 ±0.01	1.19 ±0.01	1.97 ±0.01	1.34 ±0.10
Treatment 1976–1981	0.68 ±0.07	0.51 ±0.07	0.69 ±0.07	0.65 ±0.10
Percent change	−49 ±8	−57 ±10	−65 ±6	−51 ±11
		Spring		
Pretreatment 1968–1971	1.22 ±0.09	0.99 ±0.09	1.74 ±0.09	1.17 ±0.12
Treatment 1976–1981	0.62 ±0.07	0.51 ±0.07	0.56 ±0.07	0.59 ±0.09
Percent change	−49 ±9	−49 ±15	−68 ±7	−49 ±13

The water temperature changed in both sections during the study and an analysis of the net change (treated minus control) was done to show more clearly the temperature change in the treated section relative to the control. Temperatures during the treatment period in the treated section averaged 0.3°F warmer during October–February, 1.8°F warmer during March–September, and 2.7°F warmer during June–August than during the pretreatment period. Because the water temperature increased in both sections during October–February and the average increase in both sections exceeded 1°F for several of the months, the net temperature increase of 0.3°F was not significant. On the other hand, the March–September temperature increase occurred in the treated section despite a concurrent temperature decrease in the control section. We attributed the net average increase of 1.8°F (and 2.7°F, in June–August) to the effects of the wider and shallower stream. These increases were statistically significant ($P = 0.05$). The greater surface area and shallower water of the stream apparently resulted in higher water temperatures.

Biological Results

Brook Trout Population Changes

The brook trout population remained relatively stable in the control section of Hunt Creek throughout the experiment. The number of brook trout present by age group and their survival rate (slope of curve) changed little over the years (Figure 8). By contrast, a major decrease occurred in the brook trout stock in the treated section of stream (Figure 8). The greatest change is evident in the survivorship curve for the 1976–1981 period, which reflects a much smaller population. We believe this curve best represents the new population status under the condition of a higher bed load. The slope of the survivorship curve is only slightly steeper than under pretreatment conditions. The biggest difference was that fewer trout were present at all ages because of less recruitment into the age-0 standing stock. This is more notable than the slightly higher death rate of the older trout.

TABLE 7.—Ratios (±95% confidence limits) of treated-to-control areas (T/C) for numbers of brook trout by age group for populations present in the fall and spring. Percent changes (±95% confidence limits) in brook trout numbers between the pretreatment (1967 or 1968–1971) and treatment (1976–1981) periods are included.

Period	Age group 0	I	II	III	IV
			Fall		
Pretreatment 1967–1971	1.46±0.07	1.03±0.07	1.31±0.07	1.80±0.07	
Treatment 1976–1981	0.72±0.07	0.50±0.07	0.47±0.07	0.54±0.07	
Percent change	−51±11	−51±16	−64±17	−70±11	
			Spring[a]		
Pretreatment 1968–1971		1.23±0.08	1.02±0.08	1.19±0.08	1.39±0.08
Treatment 1976–1981		0.68±0.07	0.48±0.07	0.36±0.07	0.44±0.07
Percent change		−45±12	−52±16	−69±16	−69±14

[a] Samples taken in the spring before annulus was formed.

We also show a survivorship curve (Figure 8) that represents the transitional years (1972–1975) of the brook trout population. Note in this curve that the numbers of age-0 through age-III brook trout (particularly age 0 through age II) are lower, whereas fish older than age III are of comparable abundance to pretreatment populations. We hypothesize that this initial drop in the population occurred because of low recruitment resulting from poor egg hatch and/or fry survival. Recruitment continued to drop as demonstrated by the difference in the number of young fish between 1972–1975 and 1976–1981. We suspect that this additional drop was caused, in part, by lower egg deposition from the smaller population of adult brook trout after about 1975.

Because of the gradual change in the brook trout population over the study period, we elected to omit the transitional years (1972–1975) from all analysis of variance tests of the population data. This allowed us to best demonstrate the difference in the brook trout stocks between the pretreatment and treatment conditions. The average number of brook trout present in the treated area decreased drastically both in fall and spring following the experimental increase in sand bed load (Table 4). These fish were only about half as numerous from 1976 to 1981, 5–10 years after the initial sediment increase, as they were in the pretreatment period. There was no such decline in the control section (Table 5). The 51% decrease in total number of brook trout was statistically significant (Table 6). The percent decrease was progressively greater for increasingly larger fish. Brook trout 2.0–4.9 in long decreased 49% whereas fish 8.0 in long or longer decreased 65%. The spring population showed a similar decline in total stock (Table 6). Again, decreases were shown to be greater for larger fish.

Grouping the fish by age rather than by size also revealed significant decreases for all age groups of brook trout in the treated section of the stream (Table 7). Declines again were evident in both the spring and fall stocks and were progressively greater for older fish.

Regression analysis of the T/C ratios for total brook trout for the years 1971 to 1981 (the years during and following sand bed-load addition) showed a statistically significant negative slope, indicating a progressive decrease in the T/C ratios over time (Figure 9). The nearly zero slope of the 1967–1975 regression indicated no change in the T/C ratios for the pretreatment brook trout population. Regression tests for the various size and age groupings indicated that statistically significant decreases in slope occurred for all groupings of brook trout in the sand-treated area. Note in Figure 9 that the population decrease was not very evident until after 1975, 4 years after the initial sediment treatment. Also note the slightly improved T/C ratio after 1980, which suggests that the population was beginning to recover. Both of these trends were evident in the T/C-ratio data sets for all size and age groupings.

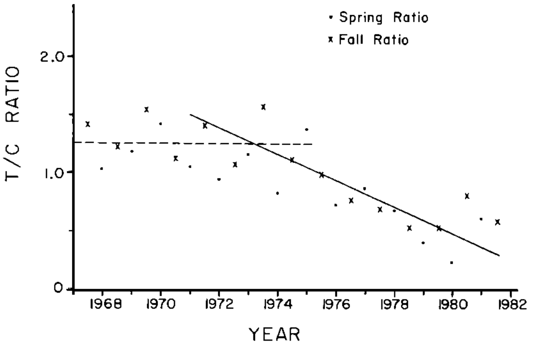

FIGURE 9.—Ratios of the total number of brook trout present in the treated area (T) divided by the total number of brook trout present in the control area (C) each spring and fall. Dashed regression line is for pretreatment ratios (1968–1975) and the solid line is for treatment ratios (1971–1981).

Similar analyses of variance and regression tests were run on the weight of brook trout present (standing biomass) for the various length and age groupings. These tests all showed statistically significant decreases in brook trout biomass for the treated reach of Hunt Creek.

Changes in Growth

We found a slight increase of 2.7% in the average length of brook trout age 0 and older during the sand treatment (Table 8). Age-0 fish were 0.1 in longer and age-V fish were 0.3 in longer. Even though these slight increases in average length proved to be statistically significant, we judged them to be nonsignificant from a practical point of view. Furthermore, even though brook trout were slightly larger at all ages, their rate of growth did not change after age 0. The only apparent change in rate of growth occurred in the first summer of life, which resulted in slightly larger age-0 fish. It is possible that growth did not increase but rather that the larger trout of the year class had better survival. We found no significant change in the length–weight relationship (or condition factor "C") of brook trout during this study.

TABLE 8.—Ratios (±95% confidence limits) of treated-to-control areas (T/C) of brook trout lengths by age group in the pretreatment and treatment periods.

Age group	Pretreatment (1967–1971)	Treatment (1976–1981)	Percent change[a]
0	1.04±0.01	1.07±0.01	+2.4±1.5*
I[b]	1.00±0.01	1.05±0.01	+4.5±1.8*
I	1.05±0.01	1.04±0.01	−0.3±1.5
II[b]	1.01±0.01	1.08±0.01	+6.9±1.8*
II	1.05±0.01	1.05±0.01	+0.3±1.5
III[b]	1.03±0.01	1.06±0.01	+3.4±1.5*
III	1.06±0.01	0.99±0.01	−6.3±1.5*
IV[b]	1.04±0.01	1.04±0.01	+0.5±1.5
IV	1.06±0.01	1.10±0.01	+3.3±1.4*
V[b]	1.08±0.01	1.22±0.01	+12.6±1.6*

[a] Asterisk denotes a significant difference ($P = 0.05$).
[b] Sample taken in the spring before annulus was formed.

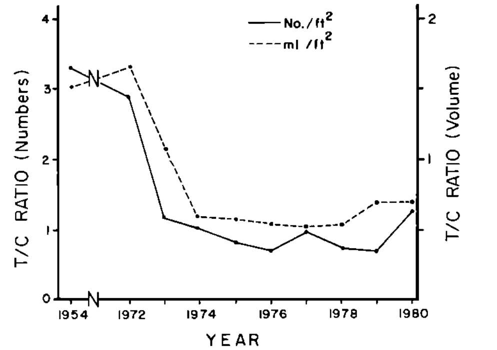

FIGURE 10.—Treated/control (T/C) ratios of numbers and volumes of invertebrates per square foot of Hunt Creek bottom.

Benthos Standing Crop

Pretreatment levels of benthos were based upon 1972 samples (the sand bed load did not reach our benthic sampling stations until 1973) and data collected in 1954 by Curry (unpublished). Based upon the T/C ratios after 1972, benthic populations dropped to less than half their pretreatment level (Figure 10)

Reduction in benthic invertebrates by taxa showed that the insect orders of Ephemeroptera, Diptera, and Coleoptera showed the most dramatic declines. Lesser reductions occurred for Trichoptera and Plecoptera. No consistent reductions in Odonata, Megaloptera, or Hemiptera were evident.

Invertebrates belonging to the taxa Annelida, Amphipoda, and Hydrocarina showed no reduction in abundance related to increased bed load. Note that numbers of benthic organisms were reduced somewhat more than volumes of organisms present per square feet of stream bottom (Figure 10), which suggests that small benthic invertebrates were affected more than large ones.

Food Consumption

Analysis of the average volume of food present per brook trout stomach showed highly variable T/C ratios and no consistent change over the study period. Based upon the fact that brook trout growth rate and condition factor did not change much during the study, it follows that the daily ration of the fish probably did not change either. Apparently less food was available for brook trout (based upon the benthos sampling) and this was offset by fewer fish. Thus, the amount of food eaten per fish did not change significantly.

Discussion

A low-gradient stream may take a long time to adjust to an input of sand-bed material. Movement rate may be a few hundred feet each month or less. The rate depends upon stream discharge, initial channel gradient, and quantity of added sediment—factors that can vary widely from stream to stream. On Hunt Creek, with an initial slope of 0.0008, the sand wave advanced at a rate of about 0.5 mi per year with the given sediment input rate. It took about 3 years for the 1-mi channel to undergo the major portion of the adjustment. However, significant changes associated with continued deposition continued on through the 4th and 5th years of the treatment.

Many changes occurred in the stream morphometry that had a negative effect on fish habitat. The stream became wider and shallower, pools filled, and the bottom became a uniform sand bed devoid of cover. These factors would make brook trout more vulnerable to predation. The reduction in static water volume, filling of pools, and reduction in channel diversity (by changing the pool–run situation to essentially one long run) all tended to reduce the carrying capacity of the stream. Deposition occurred in all areas of the stream but pools filled in the most; this resulted in an 86% reduction in the deeper areas, a major impact on fish cover.

Moving sand is the least desirable bed type from the standpoint of benthos production. Thus, the increase in sand would have an undesirable effect on the food production of food organisms.

The change from a dark silt to a sand streambed resulted in a change in albedo. The flat, relatively uniform, light-colored sandy streambed may have made the brook trout more vulnerable to predation. The decreased static water volume meant higher streamflow velocities that, together with a decrease in obstacles to break the flow, could result in a more stressful environment for fish. The impact of bed load is believed to be greatest in low-gradient streams or low-gradient sections of streams because of the greater deposition that occurs (Hansen et al. 1982).

Major changes in channel geometry occurred during the 4 years following the end of the treatment. For some characteristics, such as water surface elevation, streambed elevation, and stream width, the stream almost reverted to its initial state, but for others, such as water depth and static volume, recovery was judged to be about half completed. Of particular importance from the fisheries standpoint was the lack of stream recovery in terms of pool or channel deepening near banks. Thus, there has been a long-term reduction in fish cover that has shown little recovery in the 4 years since sand was last added to the stream.

The significant reduction of brook trout of all size and age groups in Hunt Creek has been shown to be related to the increased sand bed load. Apparently the most devastating impact on the brook trout was the reduced survival of the early life stages. We hypothesized that fry production was reduced because of degradation of microhabitat caused by sand substrate (Sandine 1974). This sand deposition on the stream bottom filled, plugged, and buried most of the rough substrate and resulted in a much smoother stream bottom.

Sand deposition also caused substantial pool filling, which eliminated most of the deeper water, undercut banks, and larger cover such as logs, branches, and cobble. This deposition transformed the stream channel into a uniform, sand-bottom canal. The end result was a stream with a more uniform gradient, greater water velocity, no pools, and less cover. As a consequence, brook trout had a poorer habitat, particularly for resting and possibly also for feeding.

Small brook trout were believed to be particularly affected because of reduced cover and increased competition for available niches. The smoother bottom probably increased visual contact and interaction between fish and thus increased territorial competition and stress. Stuart (1953), Kalleberg (1958), and Le Cren (1973) suggested that competition for territories limits the population. The loss of diverse water velocities adjacent to the stream bottom is believed to reduce the habitat that fry need for resting and energy conservation. Bjornn et al. (1977) speculated that sediment embeddedness reduced protective cover for juvenile salmonids. Kalleberg (1958) observed brown trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*) in an experimental stream and reported that increased water velocity "pressed fish toward the stream bottom" and increased their aggressiveness, which caused formation of new territories. Aggressiveness also was observed to be greatest in bottom-oriented fish, indicating that the bottom niches probably are the preferred habitat—at least for young brown trout and Atlantic salmon. The preferred resting station for brown trout was always close to a solid surface. Kalleberg's observations also indicated that brown trout and Atlantic salmon fry always selected sites where they could be in direct contact with the bottom substrate while resting. Larger fish also preferred contact with the streambed but apparently subdominant fish were excluded from it. Based upon the literature, it would seem that the ever-changing stream bottom composed of a moving sand bed load would preclude brook trout from establishing permanent territories.

Older brook trout also were forced to live in poorer habitats. Shallower water with few pools, less cover, and higher sustained velocities forced the brook trout to reside where they probably suffered greater mortality from predation. Brook trout age 0 and older in Michigan streams have been shown to suffer high losses to predacious birds, reptiles, and mammals (Alexander 1977, 1979).

The population of brook trout in Hunt Creek showed little change during the initial sand deposition in the thread of the stream but declined more quickly when the sand began depositing near the stream edge. Brook trout fry, in contrast to brown or rainbow trout (*Salmo gairdneri*) fry, appeared to be more oriented to the stream edge and water surface. The water-flow characteristics changed and thus habitat niches attractive to fry for feeding and resting were reduced.

The canal-type channel morphometry created by the greater bed load, causing more laminar flow (less turbulence), may have resulted in drifting foods being concentrated in the center of the channel more than usual and farther away from fry habitat. This could be detrimental to fry foraging.

Observations of fry behavior and stomach analyses indicate that fry feed on drift within the water column rather than foraging off the substrate. Fry in Hunt Creek eat mostly early instars of aquatic Diptera, Ephemeroptera, Trichoptera, and Plecoptera which dominate the drift.

It has been shown that higher stream velocities

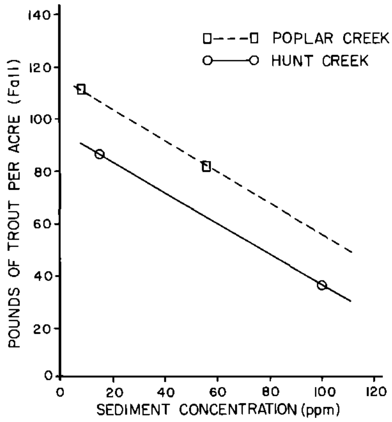

FIGURE 11.—Relationship of the fall brook trout standing crop to sand bed-load concentration in Hunt and Poplar creeks.

result in brook trout inhabiting areas closer to the bottom where velocities are lower. Fish take up stations in lower-velocity areas that are mostly near the bottom or stream edge. Any condition reducing turbulence and diversity of the water velocity within the stream cross section, we hypothesize, will force brook trout to concentrate more for feeding, particularly when they feed on drift foods. These poorer water-flow patterns may restrict the areas in which brook trout can efficiently forage for drift. Furthermore, drift foods travel through the stream much faster than normal because of the higher average water velocities and the reduction in pools and quiet water pockets along the stream edge in which they can settle. These factors, in addition to less benthic production, would reduce the food supply available to brook trout.

A related observation made during our bed-load studies was that bed-load particles and transported organic detrital particles were not mixed homogeneously throughout the water column but, rather, were concentrated in narrow bands with much of the material in contact with the streambed (Hansen 1974). We suggest that the drift organisms, which we believe are primarily subdominant, weak, or injured members of the benthic community, settle out on the streambed like sediments. Many of these drifting invertebrates may be buried by the moving sand sediment. Small brook trout that are forced to concentrate their feeding for drift in these bands farther from resting areas are subject to greater competition with their cohorts and other fish requiring the same niche. Nilsson (1967) noted that spatial segregation changed with food abundance. However, greater food density may not entirely compensate for loss of space because of the greater competition.

Another probable factor causing reduced fry production was the poorer bottom substrate for egg incubation. The presence of more sandy substrate with less permeability may have resulted in a lower hatch of deposited eggs (Cooper 1965). Furthermore, it has been shown that sand can bury brown trout redds and trap fry even though the fry have developed normally up to emergence time (Harshbarger and Porter 1979, 1982). All of these factors could reduce brook trout fry and fingerling production.

As pointed out earlier, the major effect on the population of increased bed load was reduced survival rates of the eggs or fry. Survival rates of the older brook trout changed less. However, we suggest that if the population adjustment had not taken place in the very young, it would have ultimately occurred in the older brook trout. We think survival or possible growth of older fish would have been reduced significantly. The purpose of this speculation is that if one were to mitigate the adverse effects of bed load by stocking age-0 brook trout, this might not succeed because the bed load also destroyed the carrying capacity of the stream for the older, larger fish.

Growth rates of brook trout changed little during this study. It appears that the population was brought into a new equilibrium state when the stream's carrying capacity was reduced by higher bed load; the main mechanism was a decrease in survival of the very young.

Benthic invertebrate populations, the major food supply for brook trout, were reduced about half by the increased bed load. However, the smaller food source did not have an adverse impact on the daily ration of brook trout because only half as many brook trout were present to utilize it. Sand substrate, particularly moving sand bed load, is considered the poorest substrate for habitation and production of benthic food organisms (Pennak and Van Gerpen 1947; Usinger 1968; Hynes 1970). Growth rate, condition factor, length–weight relationship, and average volume of food per brook trout stomach did not change much with increased bed load.

The increase in summer water temperature caused by the increased bed load probably had little impact on brook trout in Hunt Creek because this stream has very favorable water temperatures for trout. However, water temperature increases due to bed-load sedimentation could have major adverse effects on trout streams with marginal water temperatures.

These findings and the conclusions drawn from this Hunt Creek study are similar and consistent with findings determined from another study on bed-load manipulation in Poplar Creek, Michigan (Alexander and Hansen 1982; Hansen et al. 1982). In the Poplar Creek study, the sand bed load was reduced by a sediment basin, and the trout stock (brown trout and rainbow trout) increased significantly. Changes in vital statistics were comparable with those noted for the Hunt Creek brook trout.

From our sand bed-load studies on Hunt and Poplar creeks, we can make a rough estimate suggesting the relationship between the concentration of sand bed load and the fall brook trout standing crop per acre. Our predictive lines for these relationships are shown in Figure 11. Note that the slopes indicating the relationship between sediment concentration and brook trout standing crop are similar for Hunt Creek and Poplar Creek. An increase in bed-load sediment of about 17 ppm will result in a 10-lb/acre decrease in standing crop of brook trout.

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